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A weak dichotomy below $\mathsf{E}_1 \times \mathsf{E}_3$

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ABSTRACT

We prove that if E is an equivalence relation Borel reducible to $\mathsf{E}_1 \times \mathsf{E}_3$ then either E is Borel reducible to the equality of countable sets of reals or E_1 is Borel reducible to E. The "either" case admits further strengthening.

1. Introduction

Let $\mathbb{R} = 2^{\mathbb{N}}$. Recall that E_1 and E_3 are the equivalence relations defined on the set $\mathbb{R}^{\mathbb{N}}$ as follows:

$$x \,\mathsf{E}_1\, y \quad \text{iff} \quad \exists k_0\ \forall k \geqslant k_0\ \big(x(k) = y(k)\big);$$
$$x \,\mathsf{E}_3\, y \quad \text{iff} \quad \forall k\ \big(x(k) \mathsf{E}_0\, y(k)\big);$$

where E_0 is an equivalence relation defined on $\mathbb{R}$ so that

$$a \,\mathsf{E}_0\, b \quad \text{iff} \quad \exists n_0\ \forall n \geqslant n_0\ \big(a(n) = b(n)\big).$$

The equivalence E_3 is often denoted as $(\mathsf{E}_0)^\omega$.

Kechris and Louveau in [10] and Hjorth and Kechris in [3,4] proved that any Borel equivalence relation E satisfying $\mathsf{E} <_{\mathrm{B}} \mathsf{E}_1$, resp., $\mathsf{E} <_{\mathrm{B}} \mathsf{E}_3$, also satisfies the non-strict $\mathsf{E} \leqslant_{\mathrm{B}} \mathsf{E}_0$. Here $<_{\mathrm{B}}$ and $\leqslant_{\mathrm{B}}$ are resp. strict and non-strict relations of Borel reducibility. Thus if E is an equivalence relation on a Borel set X[2] and F is an equivalence relation on a Borel set Y then $\mathsf{E} \leqslant_{\mathrm{B}} \mathsf{F}$ means that there exists a Borel map $\vartheta : X \to Y$ such that

$$x \,\mathsf{E}\, x' \quad \Longleftrightarrow \quad \vartheta(x)\, \mathsf{F}\, \vartheta(x')$$

holds for all $x, x' \in X$. Such a map ϑ is called a (Borel) *reduction* of E to F. If both $\mathsf{E} \leqslant_{\mathrm{B}} \mathsf{F}$ and $\mathsf{F} \leqslant_{\mathrm{B}} \mathsf{E}$ then they write $\mathsf{E} \approx_{\mathrm{B}} \mathsf{F}$ (Borel *bi-reducibility*), while $\mathsf{E} <_{\mathrm{B}} \mathsf{F}$ (strict reducibility) means that $\mathsf{E} \leqslant_{\mathrm{B}} \mathsf{F}$ but not $\mathsf{F} \leqslant_{\mathrm{B}} \mathsf{E}$. See the cited papers [3,4] or *e.g.* [2,9] on various aspects of Borel reducibility in set theory and mathematics in general.

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[2] We consider only Borel sets in Polish spaces.

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The above mentioned results give a complete description of the $\leqslant_B$-structure of Borel equivalence relations below E_1 and below E_3. It is then a natural step to investigate the $\leqslant_B$-structure below E_{13}, where $\mathsf{E}_{13} = \mathsf{E}_1 \times \mathsf{E}_3$ is the product of E_1 and E_3, that is, an equivalence on $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ defined so that for any points $\langle x, \xi\rangle$ and $\langle y, \eta\rangle$ in $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $\langle x, \xi\rangle \mathsf{E}_{13} \langle y, \eta\rangle$ if and only if $x \mathsf{E}_1 y$ and $\xi \mathsf{E}_3 \eta$.

The intended result would be that the $\leqslant_B$-cone below E_{13} includes the cones determined separately by E_1 and E_3, together with the disjoint union of E_1 and E_3 (*i.e.*, the union of E_1 and E_3 defined on two disjoint copies of $\mathbb{R}^{\mathbb{N}}$), E_{13} itself, and nothing else. This is however a long shot. The following theorem, the main result of this note, can be considered as a small step in this direction.

Theorem 1. *Suppose that* E *is a Borel equivalence relation and* $\mathsf{E} \leqslant_B \mathsf{E}_{13}$. *Then* **either** E *is Borel reducible to* T_2 **or** $\mathsf{E}_1 \leqslant_B \mathsf{E}$.

Recall that the equivalence relation T_2, known as "the equality of countable sets of reals", is defined on $\mathbb{R}^{\mathbb{N}}$ so that $x \mathsf{T}_2 y$ iff $\{x(n)\colon n \in \mathbb{N}\} = \{y(n)\colon n \in \mathbb{N}\}$. It is known that $\mathsf{E}_3 <_B \mathsf{T}_2$ strictly, and there exist many Borel equivalence relations E satisfying $\mathsf{E} <_B \mathsf{T}_2$ but incomparable with E_3: for instance non-hyperfinite Borel countable ones like E_∞. The two cases are incompatible because E_1 is known not to be Borel reducible to orbit equivalence relations of Polish actions (to which class T_2 belongs).

A rather elementary argument reduces Theorem 1 to the following:

Theorem 2. *Suppose that* $P_0 \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ *is a Borel set. Then* **either** *the equivalence* $\mathsf{E}_{13} \restriction P_0$ *is Borel reducible to* T_2 **or** $\mathsf{E}_1 \leqslant_B \mathsf{E}_{13} \restriction P_0$.

Indeed suppose that Z (a Borel set) is the domain of E, and $\vartheta : Z \to \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ is a Borel reduction of E to E_{13}. Let $f : Z \to 2^{\mathbb{N}} = \mathbb{R}$ be an arbitrary Borel injection. Define another reduction $\vartheta' : Z \to \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ as follows. Suppose that $z \in Z$ and $\vartheta(z) = \langle x, \xi\rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$. Put $\vartheta'(z) = \langle x', \xi\rangle$, where x', still a point in $\mathbb{R}^{\mathbb{N}}$, is related to x so that $x'(n) = x(n)$ for all $n \geqslant 1$ but $x'(0) = f(z)$. Then obviously $\vartheta(z)$ and $\vartheta'(z)$ are E_{13}-equivalent for all $z \in Z$, and hence ϑ' is still a Borel reduction of E to E_{13}. On the other hand, ϑ' is an injection (because so is f). It follows that its full image $P_0 = \mathtt{ran}\,\vartheta' = \{\vartheta'(z)\colon z \in Z\}$ is a Borel set in $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, and $\mathsf{E} \approx_B \mathsf{E}_{13} \restriction P_0$.

The remainder of the paper contains the proof of Theorem 2. The partition in two cases is described in Section 3. Naturally assuming that P_0 is a lightface Δ^1_1 set, Case 1 is essentially the case when for every element $\langle x, \xi\rangle \in P_0$ (note that x, ξ are points in $\mathbb{R}^{\mathbb{N}}$) and every n we have $x(n) = F(x\restriction_{>n}, \xi\restriction_{\leqslant k}, \xi\restriction_{>k})$ for some k, where F is a Δ^1_1 function E_3-invariant w.r.t. the 3rd argument. It easily follows that then the first projection of the equivalence class $[\langle x, \xi\rangle]_{\mathsf{E}_{13}} \cap P_0$ of every point $\langle x, \xi\rangle \in P_0$ is at most countable, leading to the **either** option of Theorem 2 in Section 5.

The results of Theorems 1 and 2 in their **either** parts can hardly be viewed as satisfactory because one would expect it in the form: E is Borel reducible to E_3. Thus it is a challenging problem to replace T_2 by E_3 in the theorems. Attempts to improve the **either** option, so far rather unsuccessful, lead us to the following:

Theorem 3. *In the* **either** *case of Theorem* 2 *there exist a hyperfinite equivalence relation* G *on a Borel set* $P''_0 \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ *such that* $\mathsf{E}_{13} \restriction P_0$ *is Borel reducible to the least equivalence relation* F *on* P''_0 *which includes* G *and satisfies* $\xi \mathsf{E}_3 \eta \Longrightarrow \langle x, \xi\rangle \mathsf{F} \langle y, \eta\rangle$ *for all* $\langle x, \xi\rangle$ *and* $\langle y, \eta\rangle$ *in* P''_0.

The relation G here is induced by a countable group $\mathbb{G}$ of homeomorphisms of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ preserving the second component. (That is, if $g \in \mathbb{G}$ and $g(x, \xi) = \langle y, \eta\rangle$ then $\eta = \xi$, but y generally speaking depends on both x and ξ.) And $\mathbb{G}$ happens to be even a *locally finite* group in the sense that it is equal to the union of an increasing chain of its finite subgroups. Recall that E_3 is induced by the product group $\mathbb{H} = \langle \mathscr{P}_{\mathtt{fin}}(\mathbb{N}); \Delta\rangle^{\mathbb{N}}$ naturally acting in this case on the second factor in the product $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$. Regarding further details see Section 6.

Case 2 is treated in Sections 7 through 12. The embedding of E_1 in $\mathsf{E}_{13} \restriction P_0$ is obtained by approximately the same splitting construction as the one introduced in [10] (in the version closer to [7]).

2. Preliminaries: extension of "invariant" functions

If E is an equivalence relation on a set X then, as usual, $[x]_{\mathsf{E}} = \{y \in X\colon y \mathsf{E} x\}$ is the E-*class* of an element $x \in X$, and $[Y]_{\mathsf{E}} = \bigcup_{x\in Y} [x]_{\mathsf{E}}$ is the E-*saturation* of a set $Y \subseteq X$. A set $Y \subseteq X$ is E-*invariant* if $Y = [Y]_{\mathsf{E}}$.

The following "invariant" Separation theorem will be used below.

Proposition 4. *(5.1 in [1]) Assume that* E *is a* Δ^1_1 *equivalence relation on a* Δ^1_1 *set* $X \subseteq \mathbb{N}^{\mathbb{N}}$. *If* $A, C \subseteq X$ *are* Σ^1_1 *sets and* $[A]_{\mathsf{E}} \cap [C]_{\mathsf{E}} = \emptyset$ *then there exists an* E*-invariant* Δ^1_1 *set* $B \subseteq X$ *such that* $[A]_{\mathsf{E}} \subseteq B$ *and* $[C]_{\mathsf{E}} \cap B = \emptyset$.

Suppose that f is a map defined on a set $Y \subseteq X$. Say that f is E-*invariant* if $f(x) = f(y)$ for all $x, y \in Y$ satisfying $x \mathsf{E} y$.

Corollary 5. *Assume that* E *is a* Δ^1_1 *equivalence relation on a* Δ^1_1 *set* $A \subseteq \mathbb{N}^{\mathbb{N}}$, *and* $f : B \to \mathbb{N}^{\mathbb{N}}$ *is an* E*-invariant* Σ^1_1 *function defined on a* Σ^1_1 *set* $B \subseteq A$. *Then there exist an* E*-invariant* Δ^1_1 *function* $g : A \to \mathbb{N}^{\mathbb{N}}$ *such that* $f \subseteq g$.

Proof. It obviously suffices to define such a function on an E-invariant Δ^1_1 set Z such that $Y \subseteq Z \subseteq A$. (Then let g be just a constant on $A \smallsetminus Z$.) The set

$$P = \bigl\{\langle a, x\rangle \in A \times \mathbb{N}^{\mathbb{N}}\colon \forall b\ \bigl((b \in B \wedge a \mathrel{\mathsf{E}} b) \Longrightarrow x = f(b)\bigr)\bigr\}$$

is Π^1_1 and $f \subseteq P$. Moreover P is F-invariant, where F is defined on $A \times \mathbb{N}^{\mathbb{N}}$ so that $\langle a, x\rangle \mathrel{\mathsf{F}} \langle a', y\rangle$ iff $a \mathrel{\mathsf{E}} a'$ and $x = y$. Obviously $[f]_{\mathsf{F}} \subseteq P$. Hence by Proposition 4 there exists an F-invariant Δ^1_1 set Q such that $f \subseteq Q \subseteq P$. Then

$$R = \bigl\{\langle a, x\rangle \in Q\colon \forall y\ \bigl(y \neq x \Longrightarrow \langle a, y\rangle \notin Q\bigr)\bigr\}$$

is an F-invariant Π^1_1 set, and in fact a function, satisfying $f \subseteq R$. Applying Proposition 4 once again we end the proof. $\square$

3. An important population of Σ^1_1 functions

Working with elements and subsets of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ as the domain of the equivalence relation E_{13}, we'll typically use letters x, y, z to denote points of the first copy of $\mathbb{R}^{\mathbb{N}}$ (where E_1 lives) and letters ξ, η, ζ to denote points of the second copy of $\mathbb{R}^{\mathbb{N}}$ (where E_3 lives). Recall that, for $P \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$,

$$\mathtt{dom}\, P = \bigl\{x\colon \exists \xi\ \bigl(\langle x, \xi\rangle \in P\bigr)\bigr\} \quad \text{and} \quad \mathtt{ran}\, P = \bigl\{\xi\colon \exists x\ \bigl(\langle x, \xi\rangle \in P\bigr)\bigr\}.$$

Points of $\mathbb{R} = 2^{\mathbb{N}}$ will be denoted by a, b, c.

Assume that $x \in \mathbb{R}^{\mathbb{N}}$. Let $x{\restriction}_{>n}$, resp., $x{\restriction}_{\geqslant n}$ denote the restriction of x (as a map $\mathbb{N} \to \mathbb{R}$) to the domain (n, ∞), resp., $[n, \infty)$. Thus $x{\restriction}_{>n} \in \mathbb{R}^{>n}$, where $>n$ means the interval (n, ∞), and $x{\restriction}_{\geqslant n} \in \mathbb{R}^{\geqslant n}$, where $\geqslant n$ means $[n, \infty)$. If $X \subseteq \mathbb{R}^{\mathbb{N}}$ then put $X{\restriction}_{>n} = \{x{\restriction}_{>n}\colon x \in X\}$ and $X{\restriction}_{\geqslant n} = \{x{\restriction}_{\geqslant n}\colon x \in X\}$.

The notation connected with ${\restriction}_{<n}$ and ${\restriction}_{\leqslant n}$ is understood similarly.

Let $\xi \equiv_k \eta$ mean that $\xi \mathrel{\mathsf{E}_3} \eta$ and $\xi{\restriction}_{<k} = \eta{\restriction}_{<k}$ (that is, $\xi(j) = \eta(j)$ for all $j < k$). This is a Borel equivalence on $\mathbb{R}^{\mathbb{N}}$. A set $U \subseteq \mathbb{R}^{\mathbb{N}}$ is $\equiv_k$*-invariant* if $U = [U]_{\equiv_k}$, where $[U]_{\equiv_k} = \bigcup_{\xi \in U} [\xi]_{\equiv_k}$.

Definition 6. Let $\mathscr{F}^k_n$ denote the set of all Σ^1_1 functions[3] $\varphi : U \to \mathbb{R}$, defined on a Σ^1_1 set $U = \mathtt{dom}\,\varphi \subseteq \mathbb{R}^{>n} \times \mathbb{R}^{\mathbb{N}}$, and $\equiv_k$*-invariant* in the sense that if $\langle y, \xi\rangle$ and $\langle y, \eta\rangle$ belong to U and $\xi \equiv_k \eta$ then $\varphi(y, \xi) = \varphi(y, \eta)$.

Let ${}^{\mathrm{T}}\mathscr{F}^k_n$ denote the set of all *total* functions in $\mathscr{F}^k_n$, that is, those defined on the whole set $\mathbb{R}^{>n} \times \mathbb{R}^{\mathbb{N}}$.

Lemma 7. *If* $\varphi \in \mathscr{F}^k_n$ *then there is a* Δ^1_1 *function* $\psi \in {}^{\mathrm{T}}\mathscr{F}^k_n$ *with* $\varphi \subseteq \psi$.

Proof. Apply Corollary 5. $\square$

Definition 8. Let us fix a suitable coding system $\{W^e\}_{e \in E}$ of all Δ^1_1 sets $W \subseteq \mathbb{R} \times \mathbb{R}^{\mathbb{N}} \times \mathbb{R}$ (in particular for partial Δ^1_1 functions $\mathbb{R} \times \mathbb{R}^{\mathbb{N}} \to \mathbb{R}$), where $E \subseteq \mathbb{N}$ is a Π^1_1 set, such that there exist a Σ^1_1 relation $\boldsymbol{\Sigma}$ and a Π^1_1 relation $\boldsymbol{\Pi}$ satisfying

$$\langle b, \xi, a\rangle \in W^e \iff \boldsymbol{\Sigma}(e, b, a, \xi) \iff \boldsymbol{\Pi}(e, b, a, \xi) \tag{1}$$

whenever $e \in E$ and $a, b \in \mathbb{R}$, $\xi \in \mathbb{R}^{\mathbb{N}}$.

Let us fix a Δ^1_1 sequence of homeomorphisms $H_n : \mathbb{R} \xrightarrow{\text{onto}} \mathbb{R}^{\geqslant n}$. Put

$$\left.\begin{aligned} &W^e_n = \bigl\{\bigl\langle H_n(b), \xi, a\bigr\rangle\colon \langle b, \xi, a\rangle \in W^e\bigr\} \quad \text{for } e \in E,\\ &T = \bigl\{\langle e, k\rangle\colon e \in E \wedge W^e \text{ is a total and } {\equiv_k}\text{-invariant function}\bigr\}.\end{aligned}\right\} \tag{2}$$

Here the totality means that $\mathtt{dom}\, W^e = \mathbb{R} \times \mathbb{R}^{\mathbb{N}}$ while the invariance means that $W^e(b, \xi) = W^e(b, \eta)$ for all b, ξ, η satisfying $\xi \equiv_k \eta$.

Note that if $\langle e, k\rangle \in T$ then, for any n, W^e_n is a function in ${}^{\mathrm{T}}\mathscr{F}^k_n$, and conversely, every function in ${}^{\mathrm{T}}\mathscr{F}^k_n$ has the form W^e_n for a suitable $e \in E$.

Proposition 9. T *is a* Π^1_1 *set.*

[3] A Σ^1_1 function is a function with a Σ^1_1 graph.

Proof. Standard evaluation based on the coding of Δ^1_1 sets. $\square$

Corollary 10. *The sets*

$$\begin{aligned} S^k_n &= \{\langle x,\xi\rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}\colon \exists \varphi \in \mathscr{F}^k_n \ (x(n) = \varphi(x{\restriction}_{>n}, \xi))\} \\ &= \{\langle x,\xi\rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}\colon \exists \varphi \in {}^{\mathrm{T}}\mathscr{F}^k_n \ (x(n) = \varphi(x{\restriction}_{>n}, \xi))\} \end{aligned}$$

belong to Π^1_1 *uniformly on* n, k. *Therefore the set* $\mathbf{S} = \bigcup_m \bigcap_{n \geqslant m} \bigcup_k S^k_n$ *also belongs to* Π^1_1.

Proof. The equality of the two definitions follows from Lemma 7. The definability follows from Proposition 9 by standard evaluation. $\square$

Beginning **the proof of Theorem 2**, we can *w.l.o.g.* assume, as usual, that the Borel set P_0 in the theorem is a lightface Δ^1_1 set.

Case 1: $P_0 \subseteq \mathbf{S}$. We'll show that in this case $\mathsf{E}_{13} \restriction P_0$ is Borel reducible to T_2.
Case 2: $P_0 \setminus \mathbf{S} \neq \emptyset$. We'll prove that then $\mathsf{E}_1 \leqslant_{\mathrm{B}} \mathsf{E}_{13} \restriction P_0$.

4. Case 1: simplification

From now on and until the end of Section 5 we work under the assumptions of Case 1. The general strategy is to prove that for any $\langle x,\xi\rangle \in P_0$ there exist at most countably many points $y \in \mathbb{R}^{\mathbb{N}}$ such that, for some η, $\langle y,\eta\rangle \in P_0$ and $\langle x,\xi\rangle \mathrel{\mathsf{E}_{13}} \langle y,\eta\rangle$, and that those points can be arranged in countable sequences in a certain controlled way.

Our first goal is to somewhat simplify the picture.

Lemma 11. *There exists a* Δ^1_1 *map* $\mu : P_0 \to \mathbb{N}$ *such that for any* $\langle x,\xi\rangle \in P_0$ *we have* $\langle x,\xi\rangle \in \bigcap_{n \geqslant \mu(x,\xi)} \bigcup_k S^k_n$.

Proof. Apply Kreisel Selection to the set

$$\{\langle\langle x,\xi\rangle, m\rangle \in P_0 \times \mathbb{N}\colon \forall n \geqslant m\ \exists k\ (\langle x,\xi\rangle \in S^k_n)\}. \qquad \square$$

Let $\mathbf{0} = 0^{\mathbb{N}} \in \mathbb{R} = 2^{\mathbb{N}}$ be the constant 0: $\mathbf{0}(k) = 0$, $\forall k$. For any $\langle x,\xi\rangle \in P_0$ put $f_\mu(x,\xi) = \mathbf{0}^{\mu(x,\xi)\wedge}(x{\restriction}_{\geqslant \mu(x,\xi)})$: that is, we replace by $\mathbf{0}$ all values $x(n)$ with $n < \mu(x,\xi)$. Then $P'_0 = \{\langle f_\mu(x,\xi), \xi\rangle\colon \langle x,\xi\rangle \in P_0\}$ is a Σ^1_1 set.

Put $\mathbf{S}' = \bigcap_n \bigcup_k S^k_n$ (a Π^1_1 set by Corollary 10).

Corollary 12. *There is a* Δ^1_1 *set* P''_0 *such that* $P'_0 \subseteq P''_0 \subseteq \mathbf{S}'$. *The map* $\langle x,\xi\rangle \mapsto \langle f_\mu(x,\xi),\xi\rangle$ *is a reduction of* $\mathsf{E}_{13} \restriction P_0$ *to* $\mathsf{E}_{13} \restriction P''_0$.

Proof. Obviously P'_0 is a subset of the Π^1_1 set $\mathbf{S}'$. It follows that there is a Δ^1_1 set P''_0 such that $P'_0 \subseteq P''_0 \subseteq \mathbf{S}'$. To prove the second claim note that $f_\mu(x,\xi) \mathrel{\mathsf{E}_1} x$ for all $\langle x,\xi\rangle \in P_0$. $\square$

Let us fix a Δ^1_1 set P''_0 as indicated. By Corollary 12 to accomplish Case 1 it suffices to get a Borel reduction of $\mathsf{E}_{13} \restriction P''_0$ to T_2.

Lemma 13. *There exist*: *a* Δ^1_1 *sequence* $\{\kappa_n\}_{n\in\mathbb{N}}$ *of natural numbers, and a* Δ^1_1 *system* $\{F^i_n\}_{i,n\in\mathbb{N}}$ *of functions* $F^i_n \in {}^{\mathrm{T}}\mathscr{F}^{\kappa_i}_n$, *such that for all* $\langle x,\xi\rangle \in P''_0$ *and* $n \in \mathbb{N}$ *there is* $i \in \mathbb{N}$ *satisfying* $x(n) = F^i_n(x{\restriction}_{>n}, \xi)$.

Remark 14. Recall that by definition every function $F \in {}^{\mathrm{T}}\mathscr{F}^k_n$ is invariant in the sense that if $\langle x,\xi\rangle$ and $\langle x,\eta\rangle$ belong to $\mathbb{R}^{>n} \times \mathbb{R}^{\mathbb{N}}$, $\xi{\restriction}_{<k} = \eta{\restriction}_{<k}$, and $\xi \mathrel{\mathsf{E}_3} \eta$, then $\varphi(x,\xi) = \varphi(x,\eta)$. This allows us to sometimes use the notation like $F^i_n(x{\restriction}_{>n}, \xi{\restriction}_{<k}, \xi{\restriction}_{\geqslant k})$, where $k = \kappa_i$, instead of $F^i_n(x{\restriction}_{>n}, \xi)$, with the understanding that $F^i_n(x{\restriction}_{>n}, \xi{\restriction}_{<k}, \xi{\restriction}_{\geqslant k})$ is E_3-invariant in the 3rd argument.

In these terms, the final equality of the lemma can be re-written as $x(n) = F^i_n(x{\restriction}_{>n}, \xi{\restriction}_{<k}, \xi{\restriction}_{\geqslant k})$, where $k = \kappa_i$.

Proof of Lemma 13. By definition $P''_0 \subseteq \mathbf{S}'$ means that for any $\langle x,\xi\rangle \in P''_0$ and n there exists k such that $\langle x,\xi\rangle \in S^k_n$. The formula $\langle x,\xi\rangle \in S^k_n$ takes the form

$$\exists \varphi \in {}^{\mathrm{T}}\mathscr{F}^k_n \quad (x(n) = \varphi(x{\restriction}_{>n}, \xi)),$$

and further the form $\exists \langle e,k\rangle \in T\ (x(n) = W^e_n(x{\restriction}_{>n}, \xi))$. It follows that the Π^1_1 set

$$Z = \{\langle\langle x,\xi,n\rangle, \langle e,k\rangle\rangle \in (P_0 \times \mathbb{N}) \times T\colon x(n) = W^e_n(x{\restriction}_{>n}, \xi)\}$$

satisfies $\operatorname{dom} Z = P_0 \times \mathbb{N}$. Therefore by Kreisel Selection there is a Δ^1_1 map $\varepsilon : P_0 \times \mathbb{N} \to T$ such that $x(n) = W^e_n(x{\restriction}_{>n}, \xi)$ holds for any $\langle x, \xi\rangle \in P_0$ and n, where $\langle e, k\rangle = \varepsilon(x, \xi, n)$ for some k.

The range $R = \operatorname{ran} \varepsilon$ of this function is a Σ^1_1 subset of the Π^1_1 set T. We conclude that there is a Δ^1_1 set B such that $R \subseteq B \subseteq T$. And since $T \subseteq \mathbb{N} \times \mathbb{N}$, it follows, by some known theorems of effective descriptive set theory, that the set $\widehat{E} = \operatorname{dom} B = \{e:\ \exists k\ (\langle e, k\rangle \in B)\}$ is Δ^1_1, and in addition there exists a Δ^1_1 map $K : \widehat{E} \to \mathbb{N}$ such that $\langle e, K(e)\rangle \in B$ (and $\in T$) for all $e \in \widehat{E}$.

And on the other hand it follows from the construction that

$$\forall \langle x, \xi\rangle \in P_0\ \forall n\ \exists e \in \widehat{E}\quad \bigl(x(n) = W^e_n(x{\restriction}_{>n}, \xi)\bigr). \tag{3}$$

Let us fix any Δ^1_1 enumeration $\{e(i)\}_{i\in\mathbb{N}}$ of elements of $\widehat{E}$. Put $F^i_n = W^{e(i)}_n$. Then the last conclusion of the lemma follows from (3). Note that the functions F^i_n are uniformly Δ^1_1, $F^i_n \in {}^{\mathrm{T}}\mathscr{F}^k_n$ for some k, in particular, for $k = \kappa_i$, where $\kappa_i = K(e(i))$, and $\{\kappa_i\}_{i\in\mathbb{N}}$ is a Δ^1_1 sequence as well. $\square$

Blanket Assumption 15. *Below, we assume that the set P''_0 is chosen as above, that is, Δ^1_1 and $P''_0 \subseteq \mathbf{S}'$, while a system of functions F^i_n and a sequence $\{\kappa_i\}_{i\in\mathbb{N}}$ of natural numbers are chosen accordingly to Lemma* 13.

5. Case 1: countability of projections of equivalence classes

We prove here that in the assumption of Case 1 the equivalence $\mathsf{E}_{13} \restriction P''_0$ is Borel reducible to T_2, the equality of countable sets of reals. The main ingredient of this result will be the countability of the sets

$$C^\xi_x = \operatorname{dom}\bigl(\bigl[\langle x, \xi\rangle\bigr]_{\mathsf{E}_{13}} \cap P''_0\bigr) = \bigl\{y \in \mathbb{R}^{\mathbb{N}}:\ y\ \mathsf{E}_1\ x \wedge \exists \eta\ \bigl(\xi\ \mathsf{E}_3\ \eta \wedge \langle y, \eta\rangle \in P''_0\bigr)\bigr\},$$

where $\langle x, \xi\rangle \in P''_0$ — projections of E_{13}-classes of elements of the set P''_0.

Lemma 16. *If $\langle x, \xi\rangle \in P''_0$ then $C^\xi_x \subseteq [x]_{\mathsf{E}_1}$ and C^ξ_x is at most countable.*

Proof. That $C^\xi_x \subseteq [x]_{\mathsf{E}_1}$ is obvious. The proof of countability begins with several definitions. In fact we are going to organize elements of any set of the form C^ξ_x in a countable sequence.

Recall that $\mathbb{R} = 2^{\mathbb{N}}$. If $u \subseteq \mathbb{N}$ and $b \in \mathbb{R}$ then define $u \cdot a \in \mathbb{R}$ so that $(u \cdot a)(j) = a(j)$ whenever $j \notin u$, and $(u \cdot a)(j) = 1 - a(j)$ otherwise.

If $f \subseteq \mathbb{N} \times \mathbb{N}$ and $a \in \mathbb{R}^k$ then define $f \cdot a \in \mathbb{R}^k$ so that $(f \cdot a)(j) = (f\text{"}j) \cdot a(j)$ for all $j < k$, where $f\text{"}j = \{m:\ \langle j, m\rangle \in f\}$. Note that $f \cdot a$ depends in this case only on the restricted set $f \restriction k = \{\langle j, m\rangle \in f:\ j < k\}$.

Put $\Phi = \mathscr{P}_{\mathtt{fin}}(\mathbb{N} \times \mathbb{N})$ and $D = \bigcup_n D_n$, where for every n:

$$D_n = \bigl\{\langle a, \varphi\rangle:\ a \in \mathbb{N}^n \wedge \varphi \in \Phi^n \wedge \forall j < n\ \bigl(\varphi(j) \subseteq \kappa_{a(j)} \times \mathbb{N}\bigr)\bigr\}.$$

(The inclusion $\varphi(j) \subseteq \kappa_{a(j)} \times \mathbb{N}$ here means that the set $\varphi(j) \subseteq \mathbb{N} \times \mathbb{N}$ satisfies $\varphi(j) = \varphi(j) \restriction \kappa_{a(j)}$, that is, every pair $\langle k, l\rangle \in \varphi(j)$ satisfies $k < \kappa_{a(j)}$.)

If $\langle a, \varphi\rangle \in D_n$ and $\langle x, \xi\rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ then we define $y = \boldsymbol{\tau}^\xi_x(a, \varphi) \in \mathbb{R}^{\mathbb{N}}$ as follows: $y = \langle b_0, b_1, \dots, b_{n-1}\rangle^\wedge(x{\restriction}_{\geqslant n})$, where the reals $b_m \in \mathbb{R}$ $(m < n)$ are defined by inverse induction so that

$$b_m = F^{a(m)}_m\bigl(\langle b_{m+1}, b_{m+2}, \dots, b_{n-1}\rangle^\wedge(x{\restriction}_{\geqslant n}), \varphi(m) \cdot (\xi{\restriction}_{<\kappa_{a(m)}}), \xi{\restriction}_{\geqslant \kappa_{a(m)}}\bigr). \tag{4}$$

(See Remark 14 on notation. The element $\eta = (\varphi(m) \cdot (\xi{\restriction}_{<\kappa_{a(m)}}))^\wedge(\xi{\restriction}_{\geqslant \kappa_{a(m)}})$ belongs to $\mathbb{R}^{\mathbb{N}}$ and satisfies $\eta\ \mathsf{E}_3\ \xi$ because $\varphi(m)$ is a finite set.)

Put $\boldsymbol{\tau}^\xi_x(\Lambda, \Lambda) = x$ (Λ is the empty sequence).

Note that by definition the element $y = \boldsymbol{\tau}^\xi_x(a, \varphi) \in \mathbb{R}^{\mathbb{N}}$ satisfies $y{\restriction}_{\geqslant n} = x{\restriction}_{\geqslant n}$ provided $\langle a, \varphi\rangle \in D_n$, thus in any case $x\,\mathsf{E}_1\,\boldsymbol{\tau}^\xi_x(a, \varphi)$. Thus $\boldsymbol{\tau}^\xi_x$, the *trace* of $\langle x, \xi\rangle$, is a countable sequence, that is, a function defined on $D = \bigcup_n D_n$, a countable set, and the set $\operatorname{ran} \boldsymbol{\tau}^\xi_x = \{\boldsymbol{\tau}^\xi_x(a, \varphi):\ \langle a, \varphi\rangle \in D\}$ of all terms of this sequence is at most countable and satisfies $x = \boldsymbol{\tau}^\xi_x(\Lambda, \Lambda) \in \operatorname{ran} \boldsymbol{\tau}^\xi_x \subseteq [x]_{\mathsf{E}_1}$.

Claim 17. *Suppose that $\langle x, \xi\rangle \in P''_0$. Then $C^\xi_x \subseteq \operatorname{ran} \boldsymbol{\tau}^\xi_x$ — and hence C^ξ_x is at most countable. More exactly if $y \in C^\xi_x$ and $y{\restriction}_{\geqslant n} = x{\restriction}_{\geqslant n}$ then there is a pair $\langle a, \varphi\rangle \in D_n$ such that $y = \boldsymbol{\tau}^\xi_x(a, \varphi)$.*

We prove the second, more exact part of the claim. By definition there is $\eta \in \mathbb{R}^{\mathbb{N}}$ such that $\langle y, \eta\rangle \in P''_0$ and $\xi \mathsf{E}_3 \eta$. Put $b_m = y(m)$, $\forall m$. Note that for every $m < n$ there is a number $a(m)$ such that

$$b_m = F_m^{a(m)}\big(\langle b_{m+1},\dots,b_{n-1}\rangle^\wedge(y\restriction_{\geqslant n}),\eta\big)$$
$$= F_m^{a(m)}\big(\langle b_{m+1},\dots,b_{n-1}\rangle^\wedge(y\restriction_{\geqslant n}),\eta\restriction_{<\kappa_{a(m)}},\eta\restriction_{\geqslant\kappa_{a(m)}}\big)$$

for all $m<n$ (see Blanket Assumption 15), and hence

$$b_m = F_m^{a(m)}\big(\langle b_{m+1},\dots,b_{n-1}\rangle^\wedge(x\restriction_{\geqslant n}),\eta\restriction_{<\kappa_{a(m)}},\xi\restriction_{\geqslant\kappa_{a(m)}}\big)$$

by the invariance of functions F_m^i and because $x\restriction_{\geqslant n} = y\restriction_{\geqslant n}$. On the other hand, it follows from the assumption $\xi\,\mathsf{E}_3\,\eta$ that for every $m<n$ there is a finite set $\varphi(m)\subseteq\kappa_{a(m)}\times\mathbb{N}$ such that $\eta\restriction_{<\kappa_{a(m)}} = \varphi(m)\cdot(\xi\restriction_{<\kappa_{a(m)}})$. Then

$$b_m = F_m^{a(m)}\big(\langle b_{m+1},\dots,b_{n-1}\rangle^\wedge(x\restriction_{\geqslant n}),\varphi(m)\cdot(\xi\restriction_{<\kappa_{a(m)}}),\xi\restriction_{\geqslant\kappa_{a(m)}}\big)$$

for every $m<n$, that is, $y=\boldsymbol{\tau}_x^\xi(a,\varphi)$, as required. □ (*Claim and Lemma 16*)

The next result reduces the equivalence relation $\mathsf{E}_{13}\restriction P_0''$ to the equality of sets of the form $\operatorname{ran}\boldsymbol{\tau}_x^\xi$, that is essentially to the equivalence relation T_2 of "equality of countable sets of reals".

Corollary 18. *Suppose that $\langle x,\xi\rangle$ and $\langle y,\eta\rangle$ belong to P_0''. Then $\langle x,\xi\rangle\,\mathsf{E}_{13}\,\langle y,\eta\rangle$ holds if and only if $\xi\,\mathsf{E}_3\,\eta$ and $\operatorname{ran}\boldsymbol{\tau}_x^\xi=\operatorname{ran}\boldsymbol{\tau}_y^\eta$.*

Proof. The "if" direction is rather easy. If $\xi\,\mathsf{E}_3\,\eta$ and $\operatorname{ran}\boldsymbol{\tau}_y^\eta=\operatorname{ran}\boldsymbol{\tau}_x^\xi$ then $x\,\mathsf{E}_1\,y$ because $\operatorname{ran}\boldsymbol{\tau}_y^\eta\subseteq[y]_{\mathsf{E}_1}$ and $\operatorname{ran}\boldsymbol{\tau}_x^\xi\subseteq[x]_{\mathsf{E}_1}$ by Lemma 16.

To prove the converse suppose that $\langle x,\xi\rangle\,\mathsf{E}_{13}\,\langle y,\eta\rangle$. Then $\xi\,\mathsf{E}_3\,\eta$, of course. Furthermore, $x\,\mathsf{E}_1\,y$, therefore $x\restriction_{\geqslant n}=y\restriction_{\geqslant n}$ for an appropriate n. Let us prove that $\operatorname{ran}\boldsymbol{\tau}_y^\eta=\operatorname{ran}\boldsymbol{\tau}_x^\xi$. First of all, by definition we have $y\in C_x^\xi$, and hence (see the proof of Claim 17) there exists a pair $\langle a,\varphi\rangle\in D_n$ such that $y=\boldsymbol{\tau}_x^\xi(a,\varphi)$.

Now, let us establish $\operatorname{ran}\boldsymbol{\tau}_x^\xi=\operatorname{ran}\boldsymbol{\tau}_y^\xi$ (with one and the same ξ). Suppose that $z\in\operatorname{ran}\boldsymbol{\tau}_x^\xi$, that is, $z=\boldsymbol{\tau}_x^\xi(b,\psi)$ for a pair $\langle b,\psi\rangle\in D_m$ for some m. If $m\geqslant n$ then obviously $z=\boldsymbol{\tau}_x^\xi(b,\psi)=\boldsymbol{\tau}_y^\xi(b,\psi)$, and hence (as $x\restriction_{\geqslant n}=y\restriction_{\geqslant n}$) $z\in\operatorname{ran}\boldsymbol{\tau}_y^\xi$. If $m<n$ then $z=\boldsymbol{\tau}_x^\xi(b,\psi)=\boldsymbol{\tau}_y^\xi(a',\varphi')$, where $a'=b^\wedge(a\restriction_{\geqslant m})$ and $\varphi'=\psi^\wedge(\varphi\restriction_{\geqslant m})$, and once again $z\in\operatorname{ran}\boldsymbol{\tau}_y^\xi$. Thus $\operatorname{ran}\boldsymbol{\tau}_x^\xi\subseteq\operatorname{ran}\boldsymbol{\tau}_y^\xi$. The proof of the inverse inclusion $\operatorname{ran}\boldsymbol{\tau}_y^\xi\subseteq\operatorname{ran}\boldsymbol{\tau}_x^\xi$ is similar.

Thus $\operatorname{ran}\boldsymbol{\tau}_y^\xi=\operatorname{ran}\boldsymbol{\tau}_x^\xi$. It remains to prove $\operatorname{ran}\boldsymbol{\tau}_y^\eta=\operatorname{ran}\boldsymbol{\tau}_y^\xi$ for all y,ξ,η such that $\xi\mathsf{E}_3\eta$. Here we need another block of definitions.

Let $\mathbb{H}$ be the set of all sets $\delta\subseteq\mathbb{N}\times\mathbb{N}$ such that $\delta"j=\{m\colon \langle j,m\rangle\in\delta\}$ is finite for all $j\in\mathbb{N}$. For instance if $\xi,\eta\in\mathbb{R}^\mathbb{N}$ satisfy $\xi\mathsf{E}_3\eta$ then the set

$$\boldsymbol{\delta}_{\xi\eta}=\big\{\langle j,m\rangle\colon \xi(j)(m)\neq\eta(j)(m)\big\}$$

belongs to $\mathbb{H}$. The operation of symmetric difference Δ converts $\mathbb{H}$ into a Polish group equal to the product group $\langle\mathscr{P}_{\mathtt{fin}}(\mathbb{N});\Delta\rangle^\mathbb{N}$.

If $n\in\mathbb{N}$, $\langle a,\varphi\rangle\in D_n$, and $\delta\in\mathbb{H}$ then we define a sequence $\varphi'=H_\delta^a(\varphi)\in\Phi^n$ so that $\varphi'(m)=(\delta\restriction\kappa_{a(m)})\,\Delta\,\varphi(m)$ for every $m<n$.[4] Then the pair $\langle a,H_\delta^a(\varphi)\rangle$ obviously still belongs to D_n and $H_\delta^a(H_\delta^a(\varphi))=\varphi$.

Coming back to a triple of $y,\xi,\eta\in\mathbb{R}^\mathbb{N}$ such that $\xi\,\mathsf{E}_3\,\eta$, let $\delta=\boldsymbol{\delta}_{\xi\eta}$. A routine verification shows that $\boldsymbol{\tau}_y^\eta(a,\varphi)=\boldsymbol{\tau}_y^\xi(a,H_\delta^a(\varphi))$ for all $\langle a,\varphi\rangle\in D$. It follows that $\operatorname{ran}\boldsymbol{\tau}_y^\eta=\operatorname{ran}\boldsymbol{\tau}_y^\xi$, as required. □

Corollary 19. *The restricted relation $\mathsf{E}_{13}\restriction P_0''$ is Borel reducible to T_2.*

Proof. Since all $\boldsymbol{\tau}_x^\xi$ are countable sequences of reals, the equality $\operatorname{ran}\boldsymbol{\tau}_y^\eta=\operatorname{ran}\boldsymbol{\tau}_x^\xi$ of Corollary 18 is Borel reducible to T_2. Thus $\mathsf{E}_{13}\restriction P_0''$ is Borel reducible to $\mathsf{E}_3\times\mathsf{T}_2$ by Corollary 18. However it is known that E_3 is Borel reducible to T_2, and so does $\mathsf{T}_2\times\mathsf{T}_2$. □

□ (*Case 1 of Theorem 2*)

6. Case 1: a more elementary (?) transformation group

Here we sketch the proof of Theorem 3; see [6] for a full proof. Arguing under the assumptions of Case 1, we define a closed set

$$\boldsymbol{\Pi}=\big\{\langle x,\xi\rangle\in\mathbb{R}^\mathbb{N}\times\mathbb{R}^\mathbb{N}\colon \forall n\,\exists\langle a,\varphi\rangle\in D_n\,\big(x=\boldsymbol{\tau}_x^\xi(a,\varphi)\big)\big\}.$$

[4] Recall that $\delta\restriction k=\{\langle j,i\rangle\in\delta\colon j<k\}$.

It satisfies $P_0'' \subseteq \boldsymbol{\Pi}$ by Claim 17. Suppose that pairs $\langle a, \varphi \rangle$, $\langle b, \psi \rangle$ belong to D_n for the same n, and $\langle x, \xi \rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$. Put $G_{a\varphi}^{b\psi}(x, \xi) = \langle y, \xi \rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, where

$$y = \begin{cases} \boldsymbol{\tau}_x^{\xi}(b, \psi) & \text{whenever } x = \boldsymbol{\tau}_x^{\xi}(a, \varphi), \\ \boldsymbol{\tau}_x^{\xi}(a, \varphi) & \text{whenever } x = \boldsymbol{\tau}_x^{\xi}(b, \psi), \\ x & \text{whenever } \boldsymbol{\tau}_x^{\xi}(a, \varphi) \neq x \neq \boldsymbol{\tau}_x^{\xi}(b, \psi). \end{cases}$$

In our assumptions, $y \restriction_{\geqslant n} = x \restriction_{\geqslant n}$ and $G_{a\varphi}^{b\psi}$ is a homeomorphism of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ onto itself and of $\boldsymbol{\Pi}$ onto itself, and $G_{a\varphi}^{b\psi} = G_{b\psi}^{a\varphi}$. In addition we have $\mathtt{ran}\, \boldsymbol{\tau}_x^{\xi} = \mathtt{ran}\, \boldsymbol{\tau}_y^{\xi}$ whenever $\langle y, \xi \rangle = G_{a\varphi}^{b\psi}(x, \xi)$.

The group $\mathbb{G}$ of all superpositions of maps of the form $G_{a\varphi}^{b\psi}$, where $\langle a, \varphi \rangle$, $\langle b, \psi \rangle$ belong to one and the same set D_n, is a countable group of homeomorphisms of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$. Consider the equivalence relation G induced by $\mathbb{G}$ on $\boldsymbol{\Pi}$. Thus $\langle x, \xi \rangle \mathrel{\mathsf{G}} \langle y, \eta \rangle$ iff there exists a homeomorphism $g \in \mathbb{G}$ such that $g(x, \xi) = \langle y, \eta \rangle$ (and then by definition $\eta = \xi$).

Now let us study relations between $\mathbb{G}$ and $\mathbb{H}$, the group introduced in the proof of Corollary 18. For any $\delta \in \mathbb{H}$ define a homeomorphism H_δ of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ so that $H_\delta(x, \xi) = \langle x, \eta \rangle$, where simply $\eta = \delta \,\Delta\, \xi$ in the sense that

$$\eta(m, j) = \begin{cases} \xi(m, j) & \text{whenever } \langle m, j \rangle \notin \delta, \\ 1 - \xi(m, j) & \text{whenever } \langle m, j \rangle \in \delta. \end{cases}$$

(Then obviously $\delta = \boldsymbol{\delta}_{\xi\eta}$.) If $\gamma, \delta \in \mathbb{H}$ then the superposition $H_\delta \circ H_\gamma$ coincides with $H_{\gamma \Delta \delta}$, where Δ is the symmetric difference, as usual. Transformations of the form $G_{a\varphi}^{b\psi}$ do not commute with those of the form H_δ, yet there exists a convenient and easy to verify law of commutation:

Lemma 20. *Suppose that $n \in \mathbb{N}$ and pairs $\langle a, \varphi \rangle$ and $\langle b, \psi \rangle$ belong to D_n, and $\delta \in \mathbb{H}$. Then the superposition $G_{a\varphi}^{b\psi} \circ H_\delta$ coincides with $H_\delta \circ G_{a\varphi'}^{b\psi'}$, where $\varphi' = H_\delta^a(\varphi)$ and $\psi' = H_\delta^b(\psi)$.*

It follows that the set $\mathbb{S}$ of all homeomorphisms $s : \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}} \to \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ of the form $s = H_\delta \circ g_{\ell-1} \circ g_{\ell-2} \circ \cdots \circ g_1 \circ g_0$, where $\ell \in \mathbb{N}$, $\delta \in \mathbb{H}$, and each g_i is a homeomorphism of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ of the form $G_{a_i\varphi_i}^{b_i\psi_i}$, and the pairs $\langle a_i, \varphi_i \rangle$, $\langle b_i, \psi_i \rangle$ belong to one and the same set D_n, $n = n_i$ (then $g_{\ell-1} \circ g_{\ell-2} \circ \cdots \circ g_1 \circ g_0 \in \mathbb{G}$), — is a group under the superposition. For instance if $g = G_{a\varphi}^{b\psi}$ and g_1 belong to $\mathbb{G}$ (and $\langle a, \varphi \rangle$, $\langle b, \psi \rangle$ belong to one and the same D_n) then the superposition $H_\delta \circ g \circ H_{\delta_1} \circ g_1$ coincides with $H_\delta \circ H_{\delta_1} \circ g' \circ g_1 = H_{\delta \Delta \delta_1} \circ (g' \circ g_1)$, where $g' = G_{a\varphi'}^{b\psi'}$ and $\varphi' = H_{\delta_1}^a(\varphi)$, $\psi' = H_{\delta_1}^b(\psi)$ as in Lemma 20.

Thus $\mathbb{S}$ is a more complicated group than the direct cartesian product of $\mathbb{G}$ and $\mathbb{H}$, but on the other hand more elementary than the free product (of all formal superpositions of elements of both groups). The action of $\mathbb{S}$ on $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ is defined as follows: if s is as above then $s \cdot \langle x, \xi \rangle = H_\delta(g_{\ell-1}(g_{\ell-2}(\cdots g_1(g_0(x, \xi)) \cdots)))$. One can easily check that both the group $\mathbb{S}$ and the action are Polish. On the other hand, the induced orbit equivalence relation S is equal to the conjunction F of G and the equivalence relation E_3 acting on the 2nd factor of $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, in the sense of Theorem 3 in the Introduction.

Moreover, we have $\langle x, \xi \rangle \mathrel{\mathsf{E}_{13}} \langle y, \eta \rangle$ iff $\langle x, \xi \rangle \mathrel{\mathsf{S}} \langle y, \eta \rangle$ for any $\langle x, \xi \rangle, \langle y, \eta \rangle \in P_0''$.

The final step is the next lemma. Its proof, not really obvious, see in [6].

Lemma 21. *$\mathbb{G}$ is the union of an increasing sequence of finite subgroups, therefore the induced equivalence relation G is hyperfinite.*

$\square$ (*Theorem 3*)

The arguments above reduce further study of Case 1 of Theorem 2 to properties of the group $\mathbb{S}$ and its Polish actions. This is an open topic, and maybe the local finiteness of $\mathbb{G}$ (by Lemma 21) can lead to more comprehensive results.

7. Case 2

Then the Σ_1^1 set $R = P_0 \cap \mathbf{H}$, where $\mathbf{H} = 2^{\mathbb{N}} \smallsetminus \mathbf{S}$ is the chaotic domain, is non-empty. Our goal will be to prove that $\mathsf{E}_1 \leqslant_{\mathsf{B}} \mathsf{E}_{13} \restriction R$ in this case. The embedding $\vartheta : \mathbb{R}^{\mathbb{N}} \to R$ will have the property that any two elements $\langle x, \xi \rangle$ and $\langle x', \xi' \rangle$ in the range $\mathtt{ran}\, \vartheta \subseteq R$ satisfy $\xi \mathsf{E}_3 \xi'$, so that the ξ'-component in the range of ϑ is trivial. And as far as the x-component is concerned, the embedding will resemble the embedding defined in Case 1 of the proof of the 1st dichotomy theorem in [10] (see also [8, Ch. 8]).

Recall that sets S_n^k were defined in Corollary 10, and by definition

$$\left.\begin{array}{rll} \langle x, \xi \rangle \in \mathbf{H} & \Longrightarrow & \forall m\, \exists n \geqslant m\, \forall k\, \big(\langle x, \xi \rangle \notin S_n^k\big) \\ & \Longrightarrow & \forall m\, \exists n \geqslant m\, \forall k\, \forall \varphi \in \mathscr{F}_n^k\, \big(x(n) \neq \varphi(x \restriction_{>n}, \xi)\big) \end{array}\right\} \tag{5}$$

in Case 2. Prove a couple of related technical lemmas.

Lemma 22. *Each set S^k_n is invariant in the following sense: if $\langle x,\xi\rangle \in S^k_n$, $\langle y,\eta\rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $x{\restriction}_{\geqslant n} = y{\restriction}_{\geqslant n}$, and $\xi \mathrel{\mathsf{E}_3} \eta$ then $\langle y,\eta\rangle \in S^k_n$.*

Proof. Otherwise there is a Δ^1_1 function $\varphi \in {}^{\mathrm{T}}\mathscr{F}^k_n$ such that $y(n) = \varphi(y{\restriction}_{>n}, \eta)$. Then $x(n) = \varphi(x{\restriction}_{>n}, \eta)$ as well because $x{\restriction}_{\geqslant n} = y{\restriction}_{\geqslant n}$. We put

$$u_j = \xi(j) \mathbin{\Delta} \eta(j) = \bigl\{m\colon \xi(j)(m) \neq \eta(j)(m)\bigr\}$$

for every $j < k$, these are finite subsets of $\mathbb{N}$. If $a \in 2^{\mathbb{N}}$ and $u \subseteq \mathbb{N}$ then define $u \cdot a \in 2^{\mathbb{N}}$ so that $(u \cdot a)(m) = a(m)$ for $m \notin u$, and $(u \cdot a)(m) = a(m)$ for $m \notin u$. If $\zeta \in \mathbb{R}^{\mathbb{N}}$ then define $f(\zeta) \in \mathbb{R}^{\mathbb{N}}$ so that $f(\zeta)(j) = u_j \cdot \zeta(j)$ for $j < k$, and $f(\zeta)(j) = \zeta(j)$ for $j \geqslant k$.

Finally, put $\psi(z,\zeta) = \varphi(z, f(\zeta))$ for every $\langle z,\zeta\rangle \in \mathbb{R}^{>n} \times \mathbb{R}^{\mathbb{N}}$. The map ψ obviously belongs to ${}^{\mathrm{T}}\mathscr{F}^k_n$ together with φ. Moreover

$$x(n) = \varphi(x{\restriction}_{>n}, \eta) = \psi\bigl(x{\restriction}_{>n}, f(\eta)\bigr) = \psi(x{\restriction}_{>n}, \xi)$$

because $f(\eta){\restriction}_{<k} = \xi{\restriction}_{<k}$, and this contradicts to the choice of $\langle x,\xi\rangle$. $\square$

The next simple lemma will allow us to split Σ^1_1 sets in $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$.

Lemma 23. *If $P \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ is a Σ^1_1 set and $P \nsubseteq S^k_n$ then there exist points $\langle x,\xi\rangle$ and $\langle y,\eta\rangle$ in P with*

$$y{\restriction}_{>n} = x{\restriction}_{>n}, \quad \eta \mathrel{\mathsf{E}_3} \xi, \quad \eta{\restriction}_{<k} = \xi{\restriction}_{<k}, \quad \textit{but} \quad y(n) \neq x(n).$$

Proof. Otherwise $\psi = \{\langle\langle y{\restriction}_{>n}, \eta\rangle, y(n)\rangle\colon \langle y,\eta\rangle \in P\}$ is a map in $\mathscr{F}^k_n$, and hence $P \subseteq S^k_n$, contradiction. $\square$

8. Case 2: splitting system

We apply a splitting construction, developed in [5] for the study of "ill"founded Sacks iterations. Below, 2^n will typically denote the set of all dyadic sequences of length n, and $2^{<\omega} = \bigcup_n 2^n =$ all finite dyadic sequences.

The construction involves a map $\varphi : \mathbb{N} \to \mathbb{N}$ assuming **infinitely many** values and each its value infinitely many times (but $\operatorname{ran}\varphi$ may be a proper subset of $\mathbb{N}$), another map $\pi : \mathbb{N} \to \mathbb{N}$, and, for each $u \in 2^{<\omega}$, a non-empty Σ^1_1 subset $P_u \subseteq R = \mathbf{H} \cap P_0$ — which satisfy a quite long list of properties.

First of all, if φ is already defined at least on $[0,n)$ and $u \neq v \in 2^n$ then let $\nu_\varphi[u,v] = \max\{\varphi(\ell)\colon \ell < n \wedge u(\ell) \neq v(\ell)\}$. And put $\nu_\varphi[u,u] = -1$ for any u.

Now we present the list of requirements 1°–8°.

1°: if $\varphi(n) \notin \{\varphi(\ell)\colon \ell < n\}$ then $\varphi(n) > \varphi(\ell)$ for each $\ell < n$;
2°: if $u \in 2^n$ then $P_u \cap (\bigcup_k S^k_{\varphi(\ell)}) = \emptyset$ for each $\ell < n$;
3°: every P_u is a non-empty Σ^1_1 subset of $R \cap \mathbf{H}$;
4°: $P_{u^\wedge i} \subseteq P_u$ for all $u \in 2^{<\omega}$ and $i = 0, 1$.

Two further conditions are related rather to the sets $X_u = \operatorname{dom} P_u$.

5°: if $u, v \in 2^n$ then $X_u{\restriction}_{>\nu_\varphi[u,v]} = X_v{\restriction}_{>\nu_\varphi[u,v]}$;
6°: if $u, v \in 2^n$ then $X_u{\restriction}_{\geqslant\nu_\varphi[u,v]} \cap X_v{\restriction}_{\geqslant\nu_\varphi[u,v]} = \emptyset$.

The content of the next condition is some sort of genericity in the sense of the Gandy–Harrington forcing in the space $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, that is, the forcing notion

$$\mathbb{P} = \text{all non-empty } \Sigma^1_1 \text{ subsets of } \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}.$$

Let us fix a countable transitive model $\boldsymbol{M}$ of a sufficiently large fragment of **ZFC**.[5] For technical reasons, we assume that $\boldsymbol{M}$ is an elementary submodel of the universe w.r.t. all analytic formulas. Then simple relations between sets in $\mathbb{P}$ in the universe, like $P = Q$ or $P \subseteq Q$, are adequately reflected as the same relations between their intersections $P \cap \boldsymbol{M}$, $Q \cap \boldsymbol{M}$ with the model $\boldsymbol{M}$. In this sense $\mathbb{P}$ is a forcing notion in $\boldsymbol{M}$.

A set $D \subseteq \mathbb{P}$ is *open dense* iff, first, for any $P \in \mathbb{P}$ there is $Q \in D$, $Q \subseteq P$, and given sets $P \subseteq Q \in \mathbb{R}$, if Q belongs to D then so does P. A set $D \subseteq \mathbb{P}$ is *coded in* $\boldsymbol{M}$, iff the set $\{P \cap \boldsymbol{M}\colon P \in D\}$ belongs to $\boldsymbol{M}$. There exists at most countably many such sets because $\boldsymbol{M}$ is countable. Let us fix an enumeration (**not** in $\boldsymbol{M}$) $\{D_n\colon n \in \mathbb{N}\}$ of all open dense sets $D \subseteq \mathbb{P}$ coded in $\boldsymbol{M}$.

[5] For instance remove the Power Set axiom but add the axiom saying that for any set X there exists the set of all countable subsets of X.

The next condition essentially asserts the $\mathbb{P}$-genericity of each branch in the splitting construction over $\boldsymbol{M}$.

7°: for every n, if $u \in 2^{n+1}$ then $P_u \in D_n$.

Remark 24. It follows from 7° that for any $a \in 2^{\mathbb{N}}$ the sequence $\{P_{a\restriction n}\}_{n\in\mathbb{N}}$ is generic enough for the intersection $\bigcap_n P_{a\restriction n} \neq \emptyset$ to consist of a single point, say $\langle g(a), \gamma(a)\rangle$, and for the maps $g, \gamma : 2^{\mathbb{N}} \to \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ to be continuous.

Note that g is $1-1$. Indeed if $a \neq b$ belong to $2^{\mathbb{N}}$ then $a(n) \neq b(n)$ for some n, and hence $\nu_\varphi[a \restriction m, b \restriction m] \geqslant \varphi(n)$ for all $m \geqslant n$. It follows by 6° that $X_{a\restriction m} \cap X_{b\restriction m} = \emptyset$ for $m > n$, therefore $g(a) \neq g(b)$.

Our final requirement involves the ξ-parts of sets P_u. We'll need the following definition. Suppose that $\langle x, \xi\rangle$ and $\langle y, \eta\rangle$ belong to $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $p \in \mathbb{N}$, and $s \in \mathbb{N}^{<\omega}$, $\mathtt{lh}\, s = m$ (the length of s). Define $\langle x, \xi\rangle \cong^s_p \langle y, \eta\rangle$ iff

$$\xi \,\mathsf{E}_3\, \eta, \quad x\restriction_{>p} = y\restriction_{>p}, \quad \text{and} \quad \xi(k) \mathbin{\Delta} \eta(k) \subseteq s(k) \quad \text{for all } k < m = \mathtt{lh}\, s,$$

where $\alpha \mathbin{\Delta} \beta = \{j\colon \alpha(j) \neq \beta(j)\}$ for $\alpha, \beta \in 2^{\mathbb{N}}$. If $P, Q \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ are arbitrary sets then under the same circumstances $P \cong^s_p Q$ will mean that

$$\forall \langle x, \xi\rangle \in P\ \exists \langle y, \eta\rangle \in Q\ \bigl(\langle x, \xi\rangle \cong^s_p \langle y, \eta\rangle\bigr) \quad \text{and } \textit{vice versa}.$$

Obviously $\cong^s_p$ is an equivalence relation.

The following is the last condition:

8°: there exists a map $\pi : \mathbb{N} \to \mathbb{N}$, such that $P_u \cong^{\pi\restriction n}_{\nu_\varphi[u,v]} P_v$ holds for every n and all $u, v \in 2^n$ (and then $X_u\restriction_{>\nu_\varphi[u,v]} = X_v\restriction_{>\nu_\varphi[u,v]}$ as in 5°).

9. Case 2: splitting system implies the reducibility

Here we prove that any system of sets P_u and $X_u = \mathrm{dom}\, P_u$ and maps φ, π satisfying 1°–8° implies Borel reducibility of E_1 to $\mathsf{E}_{13} \restriction R$. This completes Case 2. The construction of such a splitting system will follow in the remainder.

Let the maps g and γ be defined as in Remark 24. Put

$$W = \bigl\{\bigl\langle g(a), \gamma(a)\bigr\rangle\colon a \in 2^{\mathbb{N}}\bigr\}.$$

Lemma 25. *W is a closed set in $\mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ and a function. Moreover if $\langle x, \xi\rangle$ and $\langle y, \eta\rangle$ belong to W then $\xi \,\mathsf{E}_3\, \eta$.*

Proof. W is closed as a continuous image of $2^{\mathbb{N}}$. That W is a function follows from the bijectivity of g, see Remark 24. Finally any two ξ, η as indikated satisfy $\xi(k) \mathbin{\Delta} \eta(k) \subseteq \pi(k)$ for all k by 8°. □

Put $X = \mathrm{dom}\, W$. Thus W is a continuous map $X \to \mathbb{R}^{\mathbb{N}}$ by the lemma.

Corollary 26. *There exists a Borel reduction of $\mathsf{E}_1 \restriction X$ to $\mathsf{E}_{13} \restriction W$.*

Proof. As W is a function, we can use the notation $W(x)$ for $x \in X = \mathrm{dom}\, W$. Put $f(x) = \langle x, W(x)\rangle$. This is a Borel, even a continuous map $X \to W$. It remains to establish the equivalence

$$x \,\mathsf{E}_1\, y \iff f(x) \mathsf{E}_{13} f(y) \quad \text{for all } x, y \in X. \tag{6}$$

If $x \,\mathsf{E}_1\, y$ then $W(x) \mathsf{E}_3 W(y)$ by Lemma 25, and hence easily $f(x) \mathsf{E}_{13} f(y)$. If $x \,\mathsf{E}_1\, y$ fails then obviously $f(x) \mathsf{E}_{13} f(y)$ fails, too. □

Thus to complete Case 2 it now suffices to define a Borel reduction of E_1 to $\mathsf{E}_1 \restriction X$. To get such a reduction consider the set $\varPhi = \mathrm{ran}\, \varphi$, and let $\varPhi = \{p_m\colon m \in \mathbb{N}\}$ in the increasing order; that the set $\varPhi \subseteq \mathbb{N}$ is infinite follows from 1°.

Suppose that $n \in \mathbb{N}$. Then $\varphi(n) = p_m$ for some (unique) m: we put $\psi(n) = m$. Thus $\psi : \mathbb{N} \xrightarrow{\text{onto}} \mathbb{N}$ and the preimage $\psi^{-1}(m) = \varphi^{-1}(p_m)$ is an infinite subset of $\mathbb{N}$ for any m. Define a parallel system of sets $Y_u \subseteq \mathbb{R}^{\mathbb{N}}$, $u \in 2^{<\omega}$, as follows. Put $Y_\Lambda = \mathbb{R}^{\mathbb{N}}$. Suppose that Y_u has been defined, $u \in 2^n$. Put $p = \varphi(n) = p_{\psi(n)}$. Let K be the number of all indices $\ell < n$ still satisfying $\varphi(\ell) = p$, perhaps $K = 0$. Put $Y_{u^\wedge i} = \{x \in Y_u\colon x(p)(K) = i\}$ for $i = 0, 1$.

Each of Y_u is clearly a basic clopen set in $\mathbb{R}^{\mathbb{N}}$, and one easily verifies that conditions 4°–6° are satisfied for the sets Y_u and the map ψ (instead of φ in 5°, 6°), in particular

6^*: if $u, v \in 2^n$ then $Y_u\restriction_{>\nu_\psi[u,v]} = Y_v\restriction_{>\nu_\psi[u,v]}$;
7^*: if $u, v \in 2^n$ then $Y_u\restriction_{\geqslant\nu_\psi[u,v]} \cap Y_v\restriction_{\geqslant\nu_\psi[u,v]} = \emptyset$;

where $\nu_\psi[u, v] = \max\{\psi(\ell)\colon \ell < n \wedge u(\ell) \neq v(\ell)\}$ (compare with ν_φ above).

It is clear that for any $a \in 2^{\mathbb{N}}$ the intersection $\bigcap_n Y_{a\restriction n} = \{f(a)\}$ is a singleton, and the map f is continuous and 1–1. (We can, of course, define f explicitly: $f(a)(p)(K) = a(n)$, where $n \in \mathbb{N}$ is chosen so that $\psi(n) = p$ and there is exactly K numbers $\ell < n$ with $\psi(\ell) = p$.) Note finally that $\{f(a)\colon a \in 2^{\mathbb{N}}\} = \mathbb{R}^{\mathbb{N}}$ since by definition $Y_{u^\wedge 1} \cup Y_{u^\wedge 0} = Y_u$ for all u.

We conclude that the map $\vartheta(x) = g(f^{-1}(x))$ is a continuous map (in fact a homeomorphism in this case by compactness) $\mathbb{R}^{\mathbb{N}} \xrightarrow{\text{onto}} X = \operatorname{dom} W$.

Lemma 27. *The map ϑ is a reduction of E_1 to $\mathsf{E}_1 \restriction X$, and hence ϑ witnesses $\mathsf{E}_1 \leqslant_{\mathrm{B}} \mathsf{E}_1 \restriction X$ and $\mathsf{E}_1 \leqslant_{\mathrm{B}} \mathsf{E}_{13} \restriction W$ by Corollary 26.*

Proof. It suffices to check that the map ϑ satisfies the following requirement: for each $y, y' \in \mathbb{R}^{\mathbb{N}}$ and m,

$$y\restriction_{\geqslant m} = y'\restriction_{\geqslant m} \quad \text{iff} \quad \vartheta(y)\restriction_{\geqslant p_m} = \vartheta(y')\restriction_{\geqslant p_m}. \tag{7}$$

To prove (7) suppose that $y = f(a)$ and $x = g(a) = \vartheta(y)$, and similarly $y' = f(a')$ and $x' = g(a') = \vartheta(y')$, where $a, a' \in 2^{\mathbb{N}}$. Suppose that $y\restriction_{\geqslant m} = y'\restriction_{\geqslant m}$. We then have $m > \nu_\psi[a \restriction n, a' \restriction n]$ for any n by 7*. It follows, by the definition of ψ, that $p_m > \nu_\varphi[a \restriction n, a' \restriction n]$ for any n, hence, $X_{a\restriction n}\restriction_{\geqslant p_m} = X_{a'\restriction n}\restriction_{\geqslant p_m}$ for any n by 5°. Therefore $x\restriction_{\geqslant p_m} = x'\restriction_{\geqslant p_m}$ by 7°, that is, the right-hand side of (7). The inverse implication in (7) is proved similarly. □ (*Lemma*)

It follows that we can now focus on the construction of a system satisfying 1°–8°. The construction follows in Section 12, after several preliminary lemmas in Sections 10 and 11.

10. Case 2: how to shrink a splitting system

Let us prove some results related to preservation of condition 8° under certain transformations of shrinking type. They will be applied in the construction of a splitting system satisfying conditions 1°–8° of Section 8.

Lemma 28. *Suppose that $n \in \mathbb{N}$, $s \in \mathbb{N}^{<\omega}$, and a system of Σ^1_1 sets $\emptyset \neq P_u \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $u \in 2^n$, satisfies $P_u \cong^s_{\nu_\varphi[u,v]} P_v$ for all $u, v \in 2^n$. Assume also that $w_0 \in 2^n$, and $\emptyset \neq Q \subseteq P_{w_0}$ is a Σ^1_1 set. Then the system of Σ^1_1 sets*

$$P'_u = \bigl\{\langle x, \xi\rangle \in P_u\colon \exists \langle z, \zeta\rangle \in Q \ \bigl(\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,w_0]} \langle z, \zeta\rangle\bigr)\bigr\}, \quad u \in 2^n,$$

still satisfies $P'_u \cong^s_{\nu_\varphi[u,v]} P'_v$ for all $u, v \in 2^n$, and $P'_{w_0} = Q$.

Proof. $P'_{w_0} = Q$ holds because $\nu_\varphi[w_0, w_0] = -1$. Let us verify 8°. Suppose that $u, v \in 2^n$. Each one of the three numbers $\nu_\varphi[u, w]$, $\nu_\varphi[v, w]$, $\nu_\varphi[u, v]$ is obviously not bigger than the largest of the two other numbers. This observation leads us to the following three cases.

Case a: $\nu_\varphi[u, w_0] = \nu_\varphi[u, v] \geqslant \nu_\varphi[v, w_0]$. Consider any $\langle x, \xi\rangle \in P'_u$. Then by definition there exists $\langle z, \zeta\rangle \in Q$ with $\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,w_0]} \langle z, \zeta\rangle$. Then, as $P_{w_0} \cong^s_{\nu_\varphi[v,w_0]} P_v$ is assumed by the lemma, there is $\langle y, \eta\rangle \in P_v$ such that $\langle y, \eta\rangle \cong^s_{\nu_\varphi[v,w_0]} \langle z, \zeta\rangle$. Note that $\langle z, \zeta\rangle$ witnesses $\langle y, \eta\rangle \in P'_v$. On the other hand, $\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,v]} \langle y, \eta\rangle$ because $\nu_\varphi[u, w_0] = \nu_\varphi[u, v] \geqslant \nu_\varphi[v, w_0]$. Conversely, suppose that $\langle y, \eta\rangle \in P'_v$. Then there is $\langle z, \zeta\rangle \in Q$ such that $\langle y, \eta\rangle \cong^s_{\nu_\varphi[v,w_0]} \langle z, \zeta\rangle$. Yet $P_{w_0} \cong^s_{\nu_\varphi[u,w_0]} P_u$, and hence there exists $\langle x, \xi\rangle \in P'_u$ with $\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,w_0]} \langle z, \zeta\rangle$. Once again we conclude that $\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,v]} \langle y, \eta\rangle$.

Case b: $\nu_\varphi[v, w] = \nu_\varphi[u, v] \geqslant \nu_\varphi[u, w]$. Absolutely similar to Case a.

Case c: $\nu_\varphi[u, w_0] = \nu_\varphi[v, w_0] \geqslant \nu_\varphi[u, v]$. This is a symmetric case, thus it is enough to carry out only the direction $P'_u \to P'_v$. Consider any $\langle x, \xi\rangle \in P'_u$. As above there is $\langle z, \zeta\rangle \in Q$ such that $\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,w_0]} \langle z, \zeta\rangle$. On the other hand, as $P_u \cong^s_{\nu_\varphi[u,v]} P_v$, there exists a point $\langle y, \eta\rangle \in P_v$ such that $\langle y, \eta\rangle \cong^s_{\nu_\varphi[u,v]} \langle x, \xi\rangle$. Note that $\langle z, \zeta\rangle$ witnesses $\langle y, \eta\rangle \in P'_v$: indeed by definition we have $\langle y, \eta\rangle \cong^s_{\nu_\varphi[v,w_0]} \langle z, \zeta\rangle$. □

Corollary 29. *Assume that $n \in \mathbb{N}$, $s \in \mathbb{N}^{<\omega}$, and a system of Σ^1_1 sets $\emptyset \neq P_u \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $u \in 2^n$, satisfies $P_u \cong^s_{\nu_\varphi[u,v]} P_v$ for all $u, v \in 2^n$. Assume also that $\emptyset \neq W \subseteq 2^n$, and a Σ^1_1 set $\emptyset \neq Q_w \subseteq P_w$ is defined for every $w \in W$ so that still $Q_w \cong^s_{\nu_\varphi[w,w']} Q_{w'}$ for all $w, w' \in W$. Then the system of Σ^1_1 sets*

$$P'_u = \bigl\{\langle x, \xi\rangle \in P_u\colon \forall w \in W \ \exists \langle y, \eta\rangle \in Q_w \ \bigl(\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,w]} \langle y, \eta\rangle\bigr)\bigr\}$$

still satisfies $P'_u \cong^s_{\nu_\varphi[u,v]} P'_v$ for all $u, v \in 2^n$, and $P'_w = Q_w$ for all $w \in W$.

Proof. Apply the transformation of Lemma 28 consecutively for all $w_0 \in W$ and the corresponding sets Q_{w_0}. Note that these transformations do not change the sets Q_w with $w \in W$ because $Q_w \cong^s_{\nu_\varphi[w,w']} Q_{w'}$ for all $w, w' \in W$. □

Remark 30. The sets P'_u in Corollary 29 can as well be defined by

$$P'_u = \{\langle x, \xi\rangle \in P_u\colon \exists \langle y, \eta\rangle \in Q_{w_u} \ (\langle x, \xi\rangle \cong^s_{\nu_\varphi[u,w_u]} \langle y, \eta\rangle)\}$$

where, for each $u \in 2^n$, w_u is an element of W such that the number $\nu_\varphi[u, w_u]$ is the least of all numbers of the form $\nu_\varphi[u, w]$, $w \in W$. (If there exist several $w \in W$ with the minimal $\nu_\varphi[u, w]$ then take the least of them.)

11. Case 2: how to split a splitting system

Here we consider a different question related to the construction of systems satisfying conditions 1°–8° of Section 8. Given a system of Σ^1_1 sets satisfying a 8°-like condition, how to shrink the sets so that 8° is preserved and in addition 6° holds. Let us begin with a basic technical question: given a pair of Σ^1_1 sets P, Q satisfying $P \cong^s_p Q$ for some p, s, how to define a pair of smaller Σ^1_1 sets $P' \subseteq P$, $Q' \subseteq Q$, still satisfying the same condition, but as disjoint as it is compatible with this condition.

Recall that $\operatorname{dom} P = \{x\colon \exists \xi \ (\langle x, \xi\rangle \in P)\}$ for $P \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$.

Lemma 31. *If $P, Q \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$ are non-empty Σ^1_1 sets, $p \in \mathbb{N}$, $s \in \mathbb{N}^{<\omega}$, $P \cong^s_p Q$, and $(P \cup Q) \cap S^k_p = \emptyset$, where $k = \mathtt{lh}\, s$, then there exist non-empty Σ^1_1 sets $P' \subseteq P$, $Q' \subseteq Q$ such that still $P' \cong^s_p Q'$ but in addition $(\operatorname{dom} P') {\restriction}_{\geqslant p} \cap (\operatorname{dom} Q') {\restriction}_{\geqslant p} = \emptyset$.*

Note that $P \cong^p_s Q$ implies $(\operatorname{dom} P) {\restriction}_{>p} = (\operatorname{dom} Q) {\restriction}_{>p}$.

Proof. It follows from Lemma 23 that there exist points $\langle x_0, \xi_0\rangle$ and $\langle x_1, \xi_1\rangle$ in P such that $\langle x_0, \xi_0\rangle \cong^s_p \langle x_1, \xi_1\rangle$ but $x_1(p) \neq x_0(p)$. Then there exists a number j such that, say, $x_1(p)(j) = 1 \neq 0 = x_0(p)(j)$. On the other hand, there exists $\langle y_0, \eta_0\rangle \in Q$ such that $\langle x_i, \xi_i\rangle \cong^s_p \langle y_0, \eta_0\rangle$ for $i = 0, 1$. Then $y_0(p)(j) \neq x_i(p)(j)$ for one of $i = 0, 1$. Let say $y_0(p)(j) = 0 \neq 1 = x_0(p)(j)$. Then the Σ^1_1 sets

$$P' = \{\langle x, \xi\rangle \in P\colon \exists \langle y, \eta\rangle \in Q \ (x(p)(j) = 1 \wedge y(p)(j) = 0 \wedge \langle x, \xi\rangle \cong^s_p \langle y, \eta\rangle)\};$$
$$Q' = \{\langle y, \eta\rangle \in Q\colon \exists \langle x, \xi\rangle \in P \ (x(p)(j) = 1 \wedge y(p)(j) = 0 \wedge \langle x, \xi\rangle \cong^s_p \langle y, \eta\rangle)\}$$

are Σ^1_1 and non-empty (contain resp. $\langle x_0, \xi_0\rangle$ and $\langle y_0, \eta_0\rangle$), and they satisfy $P' \cong^s_p Q'$, but $(\operatorname{dom} P') {\restriction}_{\geqslant p} \cap (\operatorname{dom} Q') {\restriction}_{\geqslant p} = \emptyset$ because $y(p)(j) = 0 \neq 1 = x(p)(j)$ whenever $\langle x, \xi\rangle \in P'$ and $\langle y, \eta\rangle \in Q'$. $\square$

Corollary 32. *Assume that $n \in \mathbb{N}$, $s \in \mathbb{N}^{<\omega}$, and a system of Σ^1_1 sets $\emptyset \neq P_u \subseteq \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $u \in 2^n$, satisfies $P_u \cong^s_{\nu_\varphi[u,v]} P_v$ for all $u, v \in 2^n$. Then there exists a system of Σ^1_1 sets $\emptyset \neq P'_u \subseteq P_u$, $u \in 2^n$, such that still $P'_u \cong^s_{\nu_\varphi[u,v]} P_v$, and in addition $(\operatorname{dom} P'_u) {\restriction}_{\geqslant \nu_\varphi[u,v]} \cap (\operatorname{dom} P'_v) {\restriction}_{\geqslant \nu_\varphi[u,v]} = \emptyset$, for all $u \neq v \in 2^n$.*

Proof. Consider any pair of $u_0 \neq v_0$ in 2^n. Apply Lemma 31 for the sets $P = P_{u_0}$ and $Q = P_{v_0}$ and $p = \nu_\varphi[u_0, v_0]$. Let P' and Q' be the Σ^1_1 sets obtained, in particular $P' \cong^s_{\nu_\varphi[u_0,v_0]} Q'$ and $(\operatorname{dom} P') {\restriction}_{\geqslant \nu_\varphi[u_0,v_0]} \cap (\operatorname{dom} Q') {\restriction}_{\geqslant \nu_\varphi[u_0,v_0]} = \emptyset$. Then by Corollary 29 there is a system of Σ^1_1 sets $\emptyset \neq P'_u \subseteq P_u$ such that still $P'_u \cong^s_{\nu_\varphi[u,v]} P'_v$ for all $u, v \in 2^n$, and $P_{u_0} = P'$, $P_{v_0} = Q'$ — and hence

$$(\operatorname{dom} P'_{u_0}) {\restriction}_{\geqslant \nu_\varphi[u_0,v_0]} \cap (\operatorname{dom} P'_{v_0}) {\restriction}_{\geqslant \nu_\varphi[u_0,v_0]} = \emptyset.$$

Take any other pair of $u_1 \neq v_1$ in 2^n and transform the system of sets P'_u the same way. Iterate this construction sufficient (finite) number of steps. $\square$

12. Case 2: the construction of a splitting system

We continue the proof of Theorem 2 — Case 2. Recall that $R = P_0 \cap \mathbf{H}$ is a Σ^1_1 set. By Lemma 27, it suffices to define functions φ and π and a system of Σ^1_1 sets $P_u \subseteq R$ together satisfying conditions 1°–8°. The construction of such a system will go on by induction on n. That is, at any step n the sets P_u with $u \in 2^n$, as well as the values of $\varphi(k)$ and $\pi(k)$ with $k < n$, will be defined.

For $n = 0$, we put $P_\Lambda = R$. ($\Lambda \in 2^0$ is the only sequence of length 0.)

Suppose that sets $P_u \subseteq R$ with $u \in 2^n$, and also all values $\varphi(\ell)$, $\ell < n$, and $\pi(k)$, $k < n$, have been defined and satisfy the applicable part of 1°–8°. The content of the inductive step $n \mapsto n + 1$ will consist in definition of $\varphi(n)$, $\pi(n)$, and sets $P_{u^\wedge i}$ with $u^\wedge i \in 2^{n+1}$, that is, $u \in 2^n$ (a dyadic sequence of length n) and $i = 0, 1$. This goes on in four Steps A, B, C, D.

12.1. Step A: definition of $\varphi(n)$

Suppose that, in the order of increase,

$$\{\varphi(\ell):\ \ell < n\} = \{p_0 < \cdots < p_m\}.$$

For $j \leqslant m$, let K_j be the number of all $\ell < n$ with $\varphi(\ell) = p_j$.

Case A: $K_j \geqslant m$ for all $j \leqslant m$. Then consider any $u_0 \in 2^n$ and an arbitrary point $\langle x_0, \xi_0\rangle \in P_{u_0}$. Note that by (5) of Section 7 there is a number $p > \max_{\ell<n} \varphi(\ell)$ such that $\langle x_0, \xi_0\rangle \notin \bigcup_k S^k_p$. Put $\varphi(n) = p$.

We claim that the sets $P'_u = P_u \setminus \bigcup_k S^k_{\varphi(n)}$ still satisfy condition 8° (and then 5° for $X'_u = \operatorname{dom} P'_u$). Indeed suppose that $u, v \in 2^n$ and $\langle x, \xi\rangle \in P'_u$. Then $\langle x, \xi\rangle \in P_u$, and hence there is a point $\langle y, \eta\rangle \in P_v$ such that $\langle x, \xi\rangle \cong^{\pi\restriction n}_{\nu_\varphi[u,v]} \langle y, \eta\rangle$. It remains to show that $\langle y, \eta\rangle \notin \bigcup_k S^k_{\varphi(n)}$. Suppose towards the contrary that $\langle y, \eta\rangle \in S^k_{\varphi(n)}$ for some k. By definition $\varphi(n) > \nu_\varphi[u, v]$, therefore $x\restriction_{\geqslant\varphi(n)} = y\restriction_{\geqslant\varphi(n)}$. It follows that $\langle x, \xi\rangle \in S^k_{\varphi(n)}$ by Lemma 22, contradiction.

Case B: If some numbers K_j are $< m$ then choose $\varphi(n)$ among p_j with the least K_j, and among them take the least one. Thus $\varphi(n) = \varphi(\ell)$ for some $\ell < n$. It follows that in this case $P_u \cap (\bigcup_k S^k_{\varphi(n)}) = \emptyset$ for all $u \in 2^n$ by the inductive assumption of 2°. Put $P'_u = P_u$.

Note that this manner of choice of $\varphi(n)$ implies 1°, 2° and also implies that φ takes infinitely many values and takes each its value infinitely many times. In addition, the construction given above proves:

Lemma 33. *There exists a system of Σ^1_1 sets $\emptyset \neq P'_u \subseteq P_u$ satisfying 8° and $P'_u \cap (\bigcup_k S^k_{\varphi(n)}) = \emptyset$ for all $u \in 2^n$.*

12.2. Step B: definition of $\pi(n)$

We work with the sets P'_u such as in Lemma 33. The next goal is to prove the following result:

Lemma 34. *There exist a number $r \in \mathbb{N}$ and a system of Σ^1_1 sets $\emptyset \neq P''_u \subseteq P'_u$ satisfying $P''_u \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u,v]} P''_v$ for all $u, v \in 2^n$.*

Proof. Let $2^n = \{u_j:\ j < K\}$ be an arbitrary enumeration of all dyadic sequences of length n; $K = 2^n$, of course. The method of proof will be to define, for any $k \leqslant K$, a number $r_k \in \mathbb{N}$ and a system of Σ^1_1 sets $\emptyset \neq Q^k_{u_j} \subseteq P'_{u_j}$, $j < k$, by induction on k so that

(∗) $Q^k_{u_i} \cong^{(\pi\restriction n)^\wedge r_k}_{\nu_\varphi[u_i,u_j]} Q^k_{u_j}$ for all $i < j < k$. (Where $(\pi \restriction n)^\wedge r$ is the extension of the finite sequence $\pi \restriction n$ by r as the new rightmost term.)

After this is done, $r = r_K$ and the sets $P''_u = Q^K_u$ prove the lemma.

We begin with $k = 2$. Then $P'_{u_0} \cong^{\pi\restriction n}_{\nu_\varphi[u_0,u_1]} P'_{u_1}$ by 8°, and hence there exist points $\langle x_0, \xi_0\rangle \in P'_{u_0}$, $\langle x_1, \xi_1\rangle \in P'_{u_1}$ such that $\langle x_0, \xi_0\rangle \cong^{\pi\restriction n}_{\nu_\varphi[u_0,u_1]} \langle x_1, \xi_1\rangle$. Then $\xi_0 \mathsf{E}_3 \xi_1$, so that there is a number $r \in \mathbb{N}$ with $\xi_0(n) \,\Delta\, \xi_1(n) \subseteq r_2$. Note that for any $p \in \mathbb{N}$ and any points $\langle x, \xi\rangle, \langle y, \eta\rangle \in \mathbb{R}^{\mathbb{N}} \times \mathbb{R}^{\mathbb{N}}$, $\langle x, \xi\rangle \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_0,u_1]} \langle y, \eta\rangle$ is equivalent to the conjunction

$$\langle x, \xi\rangle \cong^{\pi\restriction n}_{\nu_\varphi[u_0,u_1]} \langle y, \eta\rangle \wedge \xi(n) \,\Delta\, \eta(n) \subseteq r.$$

It follows that the sets

$$S_0 = \left\{\langle x, \xi\rangle \in P'_{u_0}:\ \exists \langle y, \eta\rangle \in P'_{u_1}\ \left(\langle x, \xi\rangle \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_0,u_1]} \langle y, \eta\rangle\right)\right\} \quad \text{and}$$

$$S_1 = \left\{\langle y, \eta\rangle \in P'_{u_1}:\ \exists \langle x, \xi\rangle \in P'_{u_0}\ \left(\langle x, \xi\rangle \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_0,u_1]} \langle y, \eta\rangle\right)\right\}$$

are Σ^1_1 and non-empty (contain resp. $\langle x_0, \xi_0\rangle$ and $\langle x_1, \xi_1\rangle$), and they obviously satisfy $S_0 \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_0,u_1]} S_1$. Therefore by Corollary 29 there exists a system of Σ^1_1 sets $\emptyset \neq Q^2_u \subseteq P'_u$, $u \in 2^n$, such that $Q^2_{u_0} = S_0$, $Q^2_{u_1} = S_1$, 8° still holds, and in addition $Q^2_{u_0} \cong^{(\pi\restriction n)^\wedge r_2}_{\nu_\varphi[u_0,u_1]} Q^2_{u_1}$. Put $r_2 = r$.

Now let us carry out the step $k \mapsto k+1$. Suppose that r_k and sets $Q^k_{u_j}$, $j < k$, satisfy (∗). Of all numbers $\nu_\varphi[u_j, u_k]$, $j < k$, consider the least one. Let this be, say, $\nu_\varphi[u_\ell, u_k]$, so that $\ell < k$ and $\nu_\varphi[u_\ell, u_k] \leqslant \nu_\varphi[u_j, u_k]$ for all $j < k$. As above there exists a number r and a pair of non-empty Σ^1_1 sets $S_\ell \subseteq Q^k_{u_\ell}$ and $S_k \subseteq Q^k_{u_k}$ such that $S_\ell \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_\ell,u_k]} S_k$. We can assume that $r \geqslant r_k$. Put

$$Q'_{u_j} = \left\{\langle y, \eta\rangle \in S_{u_j}:\ \exists \langle x, \xi\rangle \in S_\ell\ \left(\langle x, \xi\rangle \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_\ell,u_j]} \langle y, \eta\rangle\right)\right\}$$

for all $j < k$. The proof of Lemma 28 shows that Q'_{u_j} are non-empty Σ^1_1 sets still satisfying $(*)$ in the form of $Q'_{u_i} \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_i,u_j]} Q'_{u_j}$ for $i < j < k$ — since $r \geqslant r_k$, and obviously $Q'_{u_\ell} = S_\ell$. In addition, put $Q'_{u_k} = S_k$. Then still $Q'_{u_\ell} \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_\ell,u_k]} Q'_{u_k}$ by the choice of S_ℓ and S_k. We claim that also

$$Q'_{u_j} \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_j,u_k]} Q'_{u_k} \quad \text{for all } j < k. \tag{8}$$

Indeed we have $Q'_{u_j} \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_j,u_\ell]} Q'_{u_\ell}$ and $Q'_{u_\ell} \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_\ell,u_k]} Q'_{u_k}$ by the above. It follows that $Q'_{u_j} \cong^{(\pi\restriction n)^\wedge r}_{p} Q'_{u_k}$, where $p = \max\{\nu_\varphi[u_j,u_\ell], \nu_\varphi[u_\ell,u_k]\}$. Thus it remains to show that $p \leqslant \nu_\varphi[u_j,u_k]$. That $\nu_\varphi[u_\ell,u_k] \leqslant \nu_\varphi[u_j,u_k]$ holds by the choice of ℓ. Prove that $\nu_\varphi[u_j,u_\ell] \leqslant \nu_\varphi[u_j,u_k]$. Indeed in any case

$$\nu_\varphi[u_j,u_\ell] \leqslant \max\{\nu_\varphi[u_j,u_k], \nu_\varphi[u_\ell,u_k]\}.$$

But once again $\nu_\varphi[u_\ell,u_k] \leqslant \nu_\varphi[u_j,u_k]$, so $\nu_\varphi[u_j,u_\ell] \leqslant \nu_\varphi[u_j,u_k]$ as required.

Thus (8) is established. It follows that $Q'_{u_i} \cong^{(\pi\restriction n)^\wedge r}_{\nu_\varphi[u_i,u_j]} Q'_{u_j}$ for all $i < j \leqslant k$. We end the inductive step of the lemma by putting $r_{k+1} = r$. □ (*Lemma*)

12.3. Step C: splitting to the next level

We work with the number r and sets P''_u such as in Lemma 34. Put $\pi(n) = r$. (Recall that $\varphi(n)$ was defined at Step A.) The next step is to split each one of the sets P''_u in order to define sets $P_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, of the next splitting level.

To begin with, put $Q_{u^\wedge i} = P''_u$ for all $u \in 2^n$ and $i = 0, 1$. It is easy to verify that the system of sets $Q_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, satisfies conditions 1°–8° for the level $n+1$, except for 7° and 6°. In particular, 2° was fixed at Step A, and 8° in the form that $Q_{u^\wedge i} \cong^{\pi\restriction(n+1)}_{\nu_\varphi[u^\wedge i, v^\wedge j]} Q_{v^\wedge j}$ for all $u^\wedge i$ and $v^\wedge j$ in 2^{n+1} (and then 5° as well) at Step B — because $(\pi\restriction n)^\wedge r = \pi\restriction(n+1)$.

Recall that by definition all sets involved have no common point with $\bigcup_k S^k_{\varphi(n)}$ by 2°. Therefore Corollary 32 is applicable. We conclude that there exists a system of non-empty Σ^1_1 sets $W_{u^\wedge i} \subseteq Q_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, still satisfying 8°, and also satisfying 6°.

12.4. Step D: genericity

We have to further shrink the sets $W_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, obtained at Step C, in order to satisfy 7°, the last condition not yet fulfilled in the course of the construction. The goal is to define a new system of Σ^1_1 sets $\emptyset \neq P_{u^\wedge i} \subseteq W_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, such that still 8° holds, and in addition $P_{u^\wedge i} \in D_n$ for all $u^\wedge i \in 2^{n+1}$, where D_n is the n-th open dense subset of $\mathbb{P}$ coded in $\boldsymbol{M}$.

Take any $u_0{}^\wedge i_0 \in 2^{n+1}$. As D_n is a dense subset of $\mathbb{P}$, there exists a set $W_0 \in D_n$, therefore, a non-empty Σ^1_1 set, such that $W_0 \subseteq W_{u_0{}^\wedge i_0}$. It follows from Lemma 28 that there exists a system of non-empty Σ^1_1 sets $W'_{u^\wedge i} \subseteq W_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, still satisfying 8°, and such that $W'_{u_0{}^\wedge i_0} = Q_0$.

Now take any other $u_1{}^\wedge i_1 \neq u_0{}^\wedge i_0$ in 2^{n+1}. The same construction yields a system of non-empty Σ^1_1 sets $W''_{u^\wedge i} \subseteq W'_{u^\wedge i}$, $u^\wedge i \in 2^{n+1}$, still satisfying 8°, and such that $W''_{u_1{}^\wedge i_1} = W_1 \subseteq W'_{u_1{}^\wedge i_1}$ is a set in D_n.

Iterating this construction 2^{n+1} times, we obtain a system of sets $P_{u^\wedge i}$ satisfying 7° as well as all other conditions in the list 1°–8°, as required.

□ (*Construction and Case 2 of Theorem 2*)

□ (*Theorems 2 and 1*)

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